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An investigation of selected properties of teak wood from 9-year-old plantation forest in Indonesia

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Abstract: *An investigation of selected properties of teak wood from 9-year-old plantation in Indonesia.* Teak (*Tectona grandis* L.f) listed in standard EN 13556:2003 (code TEGR) is known as the most popular species in tropical countries, especially in Indonesia. It has not only good qualities in physical properties and mechanical properties, but it also has an aesthetics pattern. The best teak wood is usually more than 80 years old. It is too long a period of time and cannot fulfil the current wood demand. To fulfil the increasing demand, researchers in Indonesia have developed short rotation teak wood. However, the quality of this wood is rather low. The objectives of this study were to obtain complete information about mechanical, physical and acoustic properties of 9-year-old teak wood, to compare its properties with conventional teak wood and to evaluate the optimal utilization of 9 years-old teak wood based on its properties.

Keywords: teak wood, density, shrinkage, acoustic properties, modulus, strength of wood, harness, Indonesian plantation

INTRODUCTION

The fast growth of teak trees and a great interest in their wood with high natural durability, high dimensional stability and high aesthetic values (Galewski and Korzeniowski 1958, Kozakiewicz and Szkarłat 2004, Wagenführ 2007, Kozakiewicz et al. 2012) led to the creation of plantations of this species in many regions of the world, e.g. in Africa (Cameroon, Togo, Nigeria, Gabun, Tanzania), Oceania (e.g. Malaysia, Indonesia) and even Central America (e.g. Costa Rica). For example, in Indonesia, the first teak plantations were established as early as 1880. By the end of the twentieth century, about 350 thousands m^3 of teak wood were harvested annually (Varenna 1994), and currently the largest exporters of teak wood in the world are Burma and Indonesia.

Teak wood is commonly used in building construction, furniture, flooring, ship construction, veneer, etc (Galewski and Korzeniowski 1958, Kozakiewicz and Szkarłat 2004, Wagenführ 2007, Kozakiewicz et al. 2012). It is considered good if it has large diameters, straight trunk, and is without branches. The best teak wood is usually more than 80 years old (Suroso, 2018). In 2015, the production of teak wood in Indonesia was around 513 378 m^3 (Indonesia Statistics, 2015). Meanwhile, the amount of teak required as a raw material was 1.5–2.2 million m^3/year (Effendi and Dwiprabowo 2007; Roda et al.2007). To fulfil the increasing demand, researchers in Indonesia developed short rotation teak wood which could be harvested in a short period of time, i.e. less than 15 years, from community plantation forest.

Logs from short rotation teak wood have different properties than the conventional one (properties of mature wood examined and reported in literature). The short teak wood has a larger proportion of sapwood and juvenile wood (Richter et al. 2003; Darmawan et al. 2015). According to Moya et al. (2015) heartwood formation in teak wood starts in 4–6 years old. Darmawan et al. (2015) also reported that at 10-year-old teak wood, the proportion between heartwood and juvenile wood were 40% and 100%. It means that the diameter growth is around 2.5 cm/years. The wood logs with lower proportion of heartwood than the juvenile wood are of low quality (Pandit and Kurniawan, 2008). Abdurrachman and Hadjib (2006) also said that fast growing wood species from community plantation forest produced wood of low quality, not only because of age of the woods, but also because they contain more wood deflects.

The aim of this study is (1) to obtain complete information about mechanical, physical, and acoustic properties of 9-year-old teak wood, (2) to compare its properties with conventional teak wood, and (3) to evaluate the optimal utilization of 9-year-old teak wood based on its properties.

MATERIAL AND METHODS

Short rotation teak wood was obtained from community plantation forest in West Java, Indonesia. The plantation site was located at Sukabumi (7°20'31.2"S / 106°30'39.6"E, 816 m above sea level) in West Java. Sukabumi has an average annual temperature of about 28°C with dry condition and has a significant amount of rainfall during the year – about 3228 mm.

Tree seed were selected and planted at nutrient-rich sites in the community plantation forest. The tree sample was 9 years old, with height of branch-free stem ranging from 8 to 10 m, and an average diameter of 23 cm at breast height level (fig.1).

a) b)

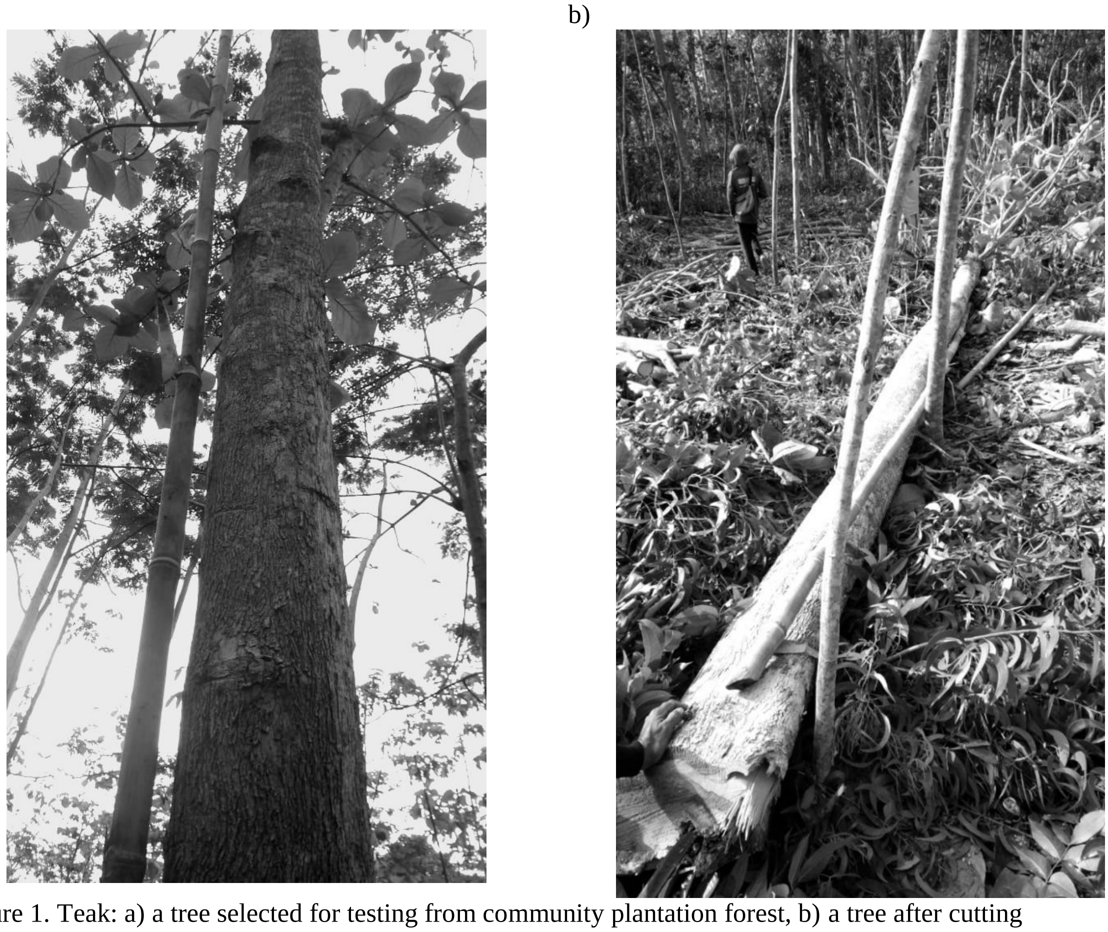

Figure 1. Teak: a) a tree selected for testing from community plantation forest, b) a tree after cutting

A wood log was divided into 3 parts (bottom, middle and top), each of them about 2 meters in length, then was cut into planks. The planks were cut into small clear samples with dimensions 20 mm x 20 mm x 300 mm for physical and mechanical properties tests (density, acoustic properties, bending strength and static modulus of elasticity (MOE_s)). After the tests, the edge sides of the samples were cut to dimensions 20 mm x 20 mm x 60 mm for another physical and mechanical properties tests (linear and volumetric shrinkage, compression strength and Brinell Hardness (HB)).

In three main groups of samples (bottom, middle and top), two subgroups (sections) were additionally distinguished (the first consisting of samples containing only heartwood and second consisting of samples containing only sapwood). The values of the tested properties were also given collectively, after combining the samples of two subgroups: hardwood and sapwood (H + S marking on figures).

The moisture content in the wood was determined in accordance with standard ISO 13061-1:2014, and wood density in accordance with standard ISO 13061-2:2014. Determination of linear shrinkage performed by using standard ISO 13061-13:2016 and volumetric shrinkage by using standard ISO 13061-14:2016. The wood was conditioned for testing density and acoustic and mechanical properties. Wood humidity after air conditioning was about 10% (± 0.9%).

Ultrasound tests were performed with the transition method, using the impulse mode of a UMT-1 materials tester. A 40 kHz head with the face radius of 40 mm was used. On the basis of previous research, appropriate settings of the device (40 dB gain, repulsion of 12Hz at pulse mode and coupling substance in the form of polyacrylic gel) were adjusted. After running ultrasound waves parallel to the grain, the time of the main echo was read and the results were used to calculate some acoustic properties of teak wood:

$$c_{\parallel} = \frac{L}{t} \tag{1}$$

where: c – velocity of the longitudinal ultrasound waves parallel to the grain [m/s]

L – sample length [m] (assuming that $L >> \lambda$)

$t = t_1 - t_0$ – real time of the passing through of the longitudinal wave [s]

t_1 – time of the passing through of the wave read from the computer screen [s]

t_0 – lag time [s]

$$MOE_d = 0.74286 \cdot c_{\parallel}^2 \cdot d \tag{2}$$

where: MOE_d – dynamic modulus of elasticity parallel to the grain [GPa]

0.74286 – reduced Poisson's ratio for wood

d – density of wood of a known moisture content [kg/m^3]

$$T = \frac{5 \cdot 10^{-8} \cdot c}{g} = \frac{5 \cdot 10^{-8}\sqrt{\frac{E}{g}}}{g} \tag{3}$$

where: T – damping of ultrasound radiation

$$Z = g \cdot c = g \cdot \sqrt{\frac{E}{g}} = \sqrt{g \cdot E} \tag{4}$$

where: Z – ultrasound wave resistant

The tests of ultimate bending strength (modulus of rupture – MOR) and the modulus of elasticity in static bending (MOE_s) were performed using standards ISO/DIS 13061-3 and ISO/DIS 13061-4. Determination of ultimate stress in compression parallel to grain was performed by using ISO/DIS 13061-17 standard. Analysis of specimens appearance after bending and compression testing was made according to ASTM D 143-94:2000.

The Brinell hardness on the longitudinal sections of teak wood was determined in accordance with the guidelines of the standard ISO 6506-1:2014. A Vexus SBRV-100D hardness tester was used for the tests with the following settings: intender – steel wheel with a diameter of 10 mm, load – 987 N, times – 15 seconds.

A statistic data analysis (average value, variation coefficient, correlation) will use Microsoft Excel 2019. The research data will be displayed in the form of tables and graphs.

RESULTS AND DISCUSSION

Moisture content of green wood

The average moisture content of green teak wood (right after cutting) depending on the zone of trunk was 79% – heartwood, 84% – heartwood and sapwood, 93% – sapwood. These results were characterized by similar variation coefficients: 10 %, 13% and 12 %, respectively.

The moisture content in heartwood was lower than in sapwood because of the cells in heartwood stop water conduction, while sapwood conducts water and contains live parenchyma cells. The moisture content average for 9-year-old teak wood's heartwood-sapwood was lower (84%) than for 5-year-old teak wood from Bogor (about 142%) (Damayanti 2016) and 14-year-old teak wood from Yogyakarta (about 95%) (Hidayati 2016). The difference in average moisture content in teak wood was due to its age and location, and perhaps also the season of the year when it was harvested. According to Bowyer et al. (2007), the moisture content of wood will decrease when its age increases. Wahyudi (2013) also reported that location of growing will also affect wood moisture content. Zawawi (2014) reported the moisture content average of 29-year-old conventional teak wood from Bogor, Indonesia had about 58.93%. It was lower than 9-year-old teak wood from Sukabumi, Indonesia (84%). The lower moisture content of wood meant that the time of wood for air-drying will be faster.

Dimensional stability (shrinkage)

Dimensional stability of 9-year-old years old teak wood could be measured by investigating its volumetric shrinkage (figure 2). The volumetric shrinkage at top part (4.8%) was higher compared to the middle part (4.5%) and bottom one (4.0%). Volumetric shrinkage in each section (top, mid, and bottom) and in each anatomical directions (tangential, radial, and longitudinal) were different because wood is an anisotropic material. Factors that could be related for the volumetric shrinkage differences were water content, density, structure anatomy of wood anatomic structure, extractive content, heartwood- and sapwood content, chemical content, and its mechanical properties.

Based on figure 2, tangential shrinkage in the top part (3.0%) was higher than in the middle part (2.8%) and the bottom part (2.6%). The microfibril structures in cell walls caused wood shrinkage to be higher in its tangential than radial and longitudinal part (Prawirohatmodjo, 2012). Tangential shrinkage average for the 9-year-old teak wood was 2.8%. It was similar to the value reported by Suwarno et al. (2000) for 15-year-old teak wood was around 3.08%. In addition, Sulistyo and Marsoem (1995) also reported tangential shrinkage at teak wood with age class IV, VI, and VII were 5.57%, 4.01% and 3.59%. However, the results were completely different with tangential shrinkage on conventional teak wood which had 5.2% (Martawijaya et al. 2005). This is due to its age and growth location.

The average of radial shrinkage of 9-year-old teak wood was 1.65%. This was not different significantly with 15-year-old teak wood that had radial shrinkage about 2.02% (Suwarno et al. 2000). In the other hand, radial shrinkage at teak wood with age class IV, VI, and VII were 3.13%, 2.3% and 2.1% (Sulistyo and Marsoem 1995). Martwijaya (2005) also reported that conventional teak wood reached radial shrinkage around 2.8%. Bowyer et al. (2007) explained that the quantity of volumetric shrinkage caused by its water content that came out through its cell wall, cell height wasn't much affected the cell while shrinking or swelling.

In general, volumetric shrinkage on its longitudinal part was around 0.3–0.4% in every section. The cellular structure between axial and radial that relatively similar caused volumetric shrinkage in its longitudinal part could not be seen. The longitudinal shrinkage average of 9-year-old teak wood was 0.33%. This is in accordance with research that Sulistyo and Marsoem (1995) did and also they reported that longitudinal shrinkage of teak wood with age class IV, VI, and VII were 0.33%, 0.41%, and 0.36%.

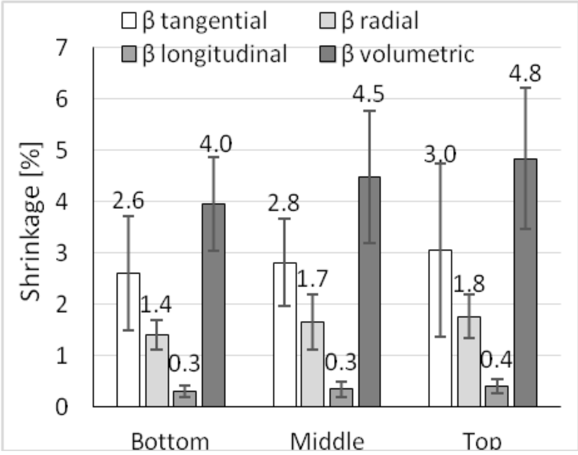

Figure 2. Volumetric shrinkage of 9-year-old teak wood in each part of the trunk

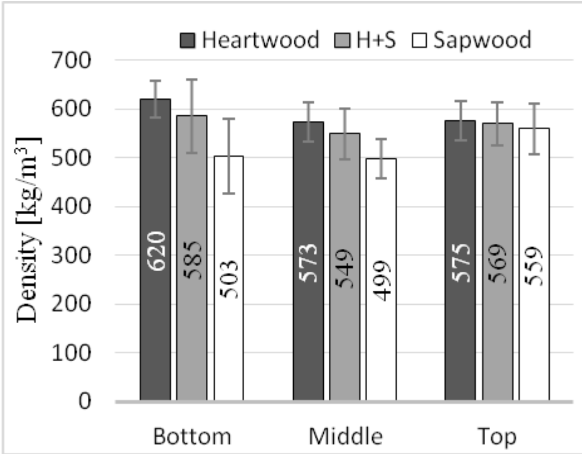

Figure 3. Density of 9-year-old teak air-dry wood in each part of the trunk

Density

Figure 3 shows the density of 9-year-old, air-dried teak wood in every part (bottom, middle and top) and every section (heartwood, heartwood and sapwood, sapwood). Based on figure 2, the density of heartwood, sapwood, and heartwood-sapwood in every part is similar. The density in the heartwood was around ± 500–600 kg/m^3, in the sapwood from 499 kg/m^3 up to 559 kg/m^3, and the heartwood-sapwood it was approximately 549 kg/m^3 up to 585 kg/m^3. The density of heartwood in every part was higher than the density of sapwood. It is natural because in the process of creating the heartwood, tylos are formed and various substances are deposited in the cells (both in the lumens and in the cell walls of).

Zawawi (2014) reported the density of conventional teak wood (29 years old) from Bogor, Indonesia to be about 780 kg/m^3. Muhran (2013) also investigated conventional teak wood that was 14 years old and reported its density was around 880 kg/m^3. Based on Zawawi (2014) and Muhran (2013), density of 9-year-old juvenile teak wood was lower than density of conventional (mature) teak wood. The proportion of heartwood which increase along with its age than sapwood caused the density becomes better.

Acoustic properties

Figure 4 shows the speed of sound result for 9-year-teak wood in each part. Velocity of ultrasound wave of 9 years teak wood were similar in each part (around 4719 m/s–5380 m/s). The middle part showed higher value but was not different significantly. Factor sound of velocity alone couldn't determine the wood quality for musical instruments (Ahmed and Adamopoulos 2018). Different musical instruments need velocity of sound on material from 3000 to 6500 m/s. It means that 9-year-old teak wood could be used as musical instruments.

Based on figure 5 that showed the MOE_d average of 9-year-old teak wood in each part was around 9.25 GPa to 11.9 GPa. The results were not significantly different in each part. For musical instruments, the MOE_d must be around 6–40 GPa. According to (Wegst 2006), 9-year-old teak wood can be suitable for soundboards (MOE_d 6–19 GPa), wind instruments (MOE_d 7–18 GPa), and violin backs (MOE_d 8–19 GPa). However, it cannot be used as piano actions (MOE_d 14–19 GPa) and xylophone bars (MOE_d 12–20 GPa).

Figure 6 showed the damping of ultrasound radiation of 9-year-old teak wood in each part. The damping of ultrasound radiation in each part was about 39 $m^4 \cdot kg^{-1} \cdot s^{-1} \cdot 10^{-8}$ to 54 $m^4 \cdot kg^{-1} \cdot s^{-1} \cdot 10^{-8}$. Differences were not statistically significant in each part. According to (Ahmed and Adamopoulus 2018), wood with the combination of higher sound velocity and low internal damping was better to transmit vibrational energy. In addition, the combination of higher MOE_d and low damping ultrasound radiation is accepted for soundboards of pianos, guitars, and violin.

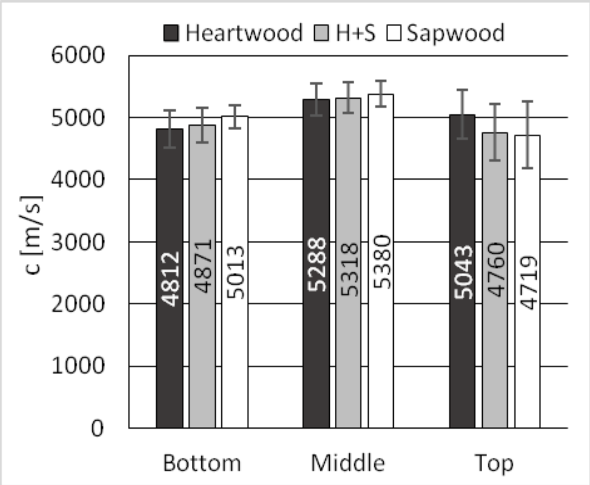

Figure 4. Velocity of ultrasound wave (c) of 9-year-old teak wood in each part of the trunk

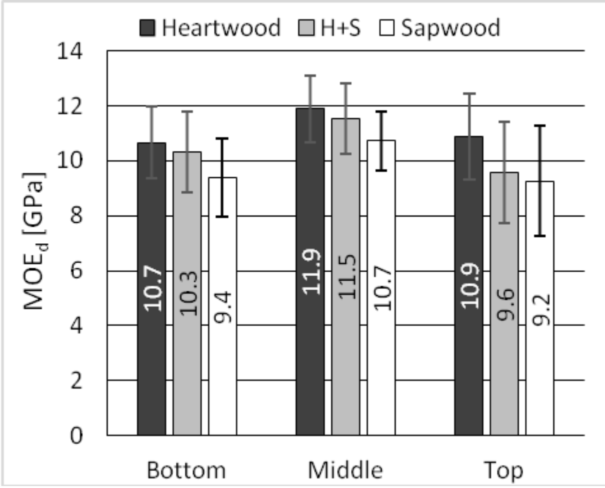

Figure 5. Dynamic modulus of elasticity (MOE_d) of 9-year-old teak wood in each part of the trunk

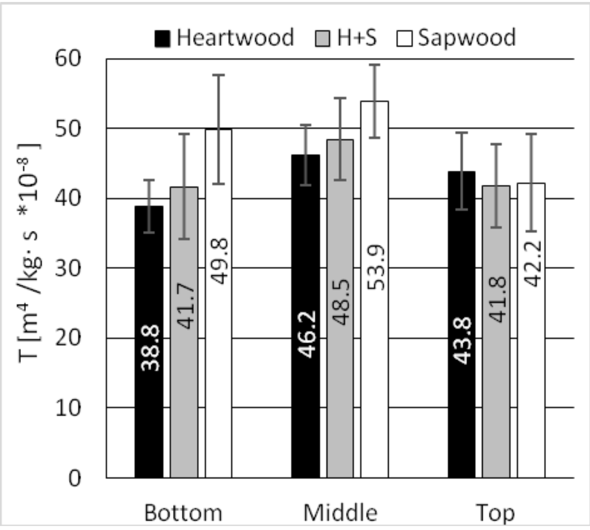

Figure 6. Damping of ultrasound radiation (T) of 9-year-old teak wood in each part of the trunk

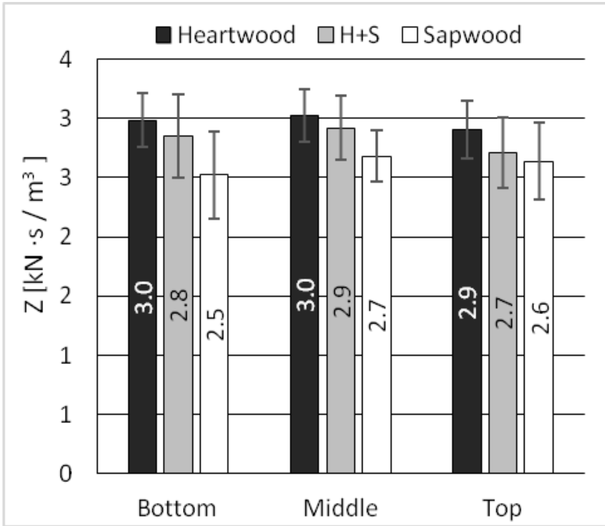

Figure 7. Ultrasound wave resistance (Z) of 9-year-old teak wood in each part of the trunk

The average of ultrasound wave resistance of 9-year-old teak wood in each part are showed in Figure 7. The ultrasound wave resistance of a material is directly affected by its MOE_d. This happened when the vibrational energy were transmitted from one medium to the other one. According to (Hilde et al. 2014), it is an important value for musical instruments with a lower Z value. Z value between 1.2 to 3.4 $kN \cdot s \cdot m^{-3}$ is available for string instruments and the higher Z value can be used as percussion instruments, such as xylophone, where longer resonance will be produced. Based on table 8, Z value for 9-year-old teak wood was around 2.5 $kN \cdot s \cdot m^{-3}$ to 3.0 $kN \cdot s \cdot m^{-3}$. Thus, even juvenile (9 years old) teak wood can be good for producing the longer resonance on musical instruments.

Mechanical properties

Figure 8 and 9 showed static modulus of elasticity (MOE_s) and bending strength (modulus of rupture – MOR) of 9 years old teak wood in each part of the trunk. The results showed that there were no significant different on MOE_s & MOR of 9-year-old teak wood in each part. The average of MOE_s in each part was around 7.65 GPa up to 10.43 GPa, and MOR was about 68.9 MPa – 123.1 MPa. Figure 5 shows that MOE_s was lower on for heartwood than sapwood. This is due to the fact that crystalline degrees of cellulose molecules, which were the main components of the cell wall, were higher in heartwood than sapwood (Amin and Dwianto 2006; Blomberg 2016).

The MOE_s average for the conventional teak wood was reported by (Martawijaya et al. 2005) to be around 12.52 GPa. MOE_s of 9-year-teak wood was lower than of the conventional one (7.65–10.43 GPa).

Figure 9 shows the MOR results for 9-year-old teak wood. The MOR of heartwood in bottom part (123.1 MPa) was higher than in the middle (111.5 MPa) and top (107.6 MPa) parts. Tsuomis (1991) and Bowyer et al. (2003) reported that increased MOR was affected by its density value. In addition, a higher wood density also increased its MOR value. Martawijaya et al. (2005) reported MOR value of conventional teak wood to be around 101.1 MPa. It showed that the MOR value for 9-year teak wood was similar to that of the conventional teak. The correlation between MOE_s & MOR for 9-year-old teak wood were around 0.8 up to 1. It means that the value of MOE_s & MOR were strongly correlated. The MOE_s value will be higher when the MOR value increases.

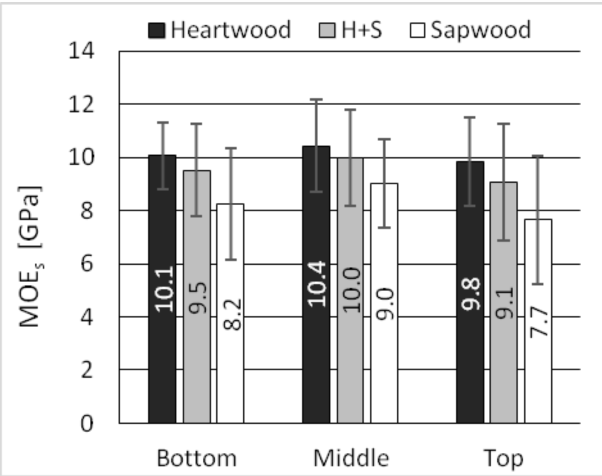

Figure 8. Static modulus of elasticity (MOE_s) of 9-year-old teak wood in each part of the trunk

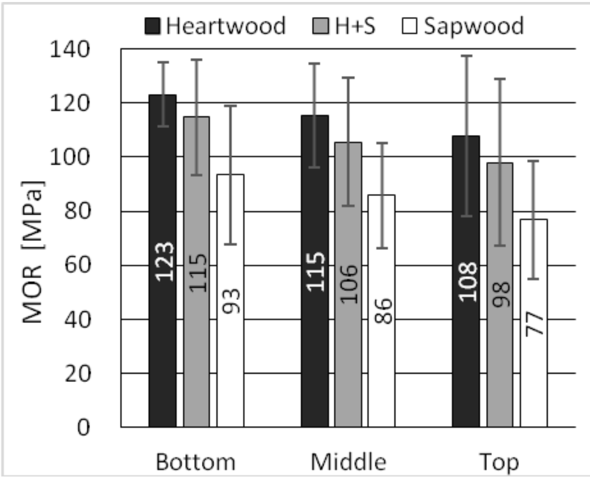

Figure 9. Bending strength – modulus of rupture (MOR) of 9-year-old teak wood in each part of the trunk

Figure 10 shows a damage pattern after MOE_s-MOR tests. The damage of samples after MOE_s-MOR tests was dominated by 3 patterns, i.e. cross-grain tension, simple tension, and brash tension, according to ASTM 143–94:2000. The percentage of cross-grain damage pattern (35.0% up to 42.5%) was higher than simple tension and brash patterns in each part of the trunk. It happened because there were skewed grain in the samples (especially sapwood) so that a damage occurred in the sloping grain in the form of diagonal grain and spiral grain below surface of the samples.

a) b) c)

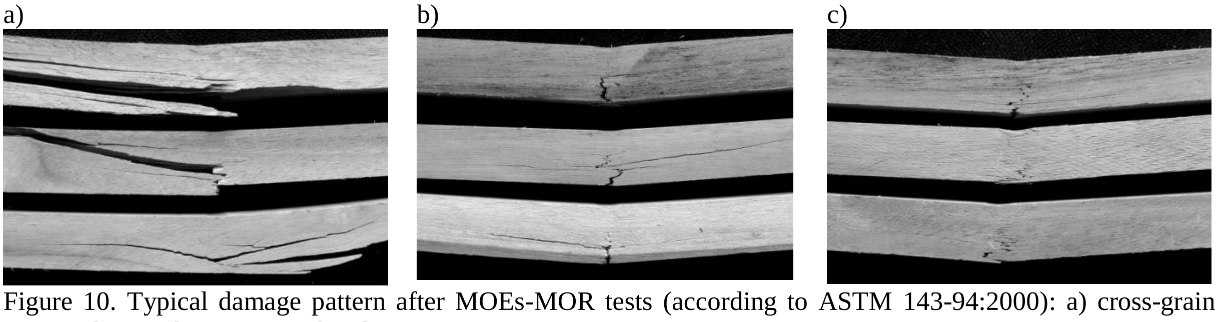

Figure 10. Typical damage pattern after MOEs-MOR tests (according to ASTM 143-94:2000): a) cross-grain tension, b) simple tension, c) brash tension

Figure 11 showed compression strength parallel to the grain of 9-year-old teak wood. The test results for this property were around 55–60 MPa in each group of the samples. The compression strength in its section (bottom, middle and top) and its part (heartwood, heartwood+sapwood, and sapwood) were not significantly different. According to Hidayati et al. (2016), compression strengths of superior teak wood and the conventional teak wood were about 42.46 MPa and 48.74 MPa. Putro and Sutjipto (1989) also reported an average compression strength parallel to the grain between 7-year-old, 17-year-old, and 27-year-old wood were 36.09 MPa, 42.95 MPa, and 48.74 MPa, respectively. In addition, Suwarno et al. (2000) reported that compression strength parallel to grain of 15-year-old conventional teak wood was 45.50 MPa. In this research, compression strength parallel to the grain of 9-year-old teak wood was similar to that of the superior teak wood and the conventional teak wood (Hidayati et al. 2016).

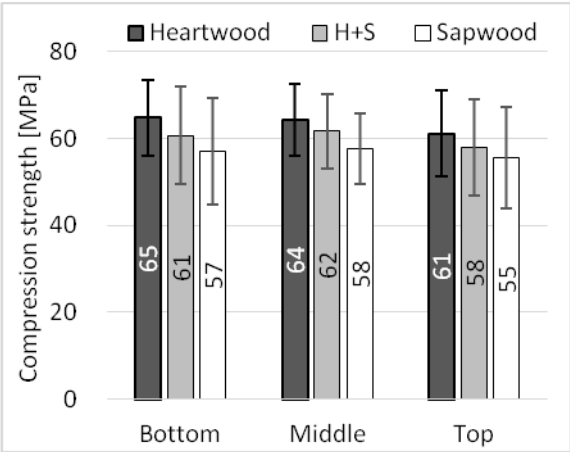

Figure 11. Compression strength of 9-year-old teak wood in each part of the trunk

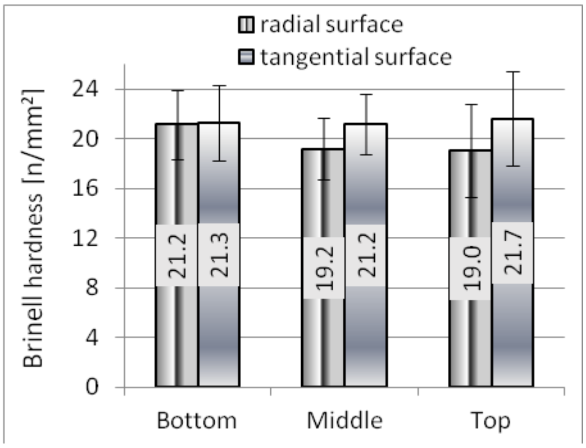

Figure 12. Brinell hardness of 9-year-old teak wood in each part of the trunk

Two types of failures (according to ASTM 143-94:2000) dominated in the tested samples after the compression tests: “wedge split” (the direction of the split – radial or tangential – shall be noted) and “shearing” (the plane rupture makes an angle of more than 45° with the top of specimen). These are typical damages characteristic of straight-grained air-dried wood of medium density (Kozakiewicz 2010). There was a “compression and shearing parallel to grain” type of damage (cross-grained pieces and shall be the basis for the culling of the specimen) in individual cases (samples with deflected fibres), too. There were no differences in the frequency of damage types depending on the trunk part or zone of wood (heartwood, sapwood).

Figure 12 shows the result of Brinell hardness of juvenile teak wood in each part of trunk divided into radial and tangential sections. The hardness of the tangential section is slightly greater than that of the radial section in general, but there is only a significant difference in the middle and top parts of the trunk. The hardness of 9-year-old teak wood ranges from 19 to 22 N/mm^2 and it is similar to the average value of 4-year-old teak wood (20.8 N/mm^2 – Wahyudi et al. 2014). The hardness of mature teak wood can be twice as high (Martawijaya et al. 2005, Rizanti et al. 2018). The lower hardness is a certain limitation in the willingness to use juvenile wood for flooring materials.

A 9-year-old teak trunk contains a lot of sapwood which it its disadvantage. Sapwood has significantly lower durability compared to heartwood and therefore, without impregnation, it cannot be used outdoors in contact with the ground. This is another limitation for the use of juvenile wood.

The examined mechanical properties (MOEs, MOR, compression strength and Brinell hardness) are correlated with wood density. However, these dependencies are not always strong. The following is an example of the compressive strength. In general, bottom and middle part showed positively correlation between density and compression strength parallel to grain because the results closed to 1. However in top part the results did not show any significant correlation between these properties (value less than 0.5). It could be caused of most heartwood in the top part still contained sapwood so the differences between correlation density and compression strength in heartwood and sapwood in the top part could not be seen clearly. According to Adetayo and Dahunsi (2017), density and compression strength of wood were correlated positively each other. The higher density of wood will increase its compression strength.

CONCLUSIONS

Based on the research of juvenile teak wood from a plantation forest in Indonesia, the following conclusions were made:

1. Physical properties of 9-year-old teak wood were inferior to those of mature (conventional) teak wood with higher moisture content of around 84% and lower density. In addition, the density of its heartwood was higher than its sapwood. Dimensional stability test results carried out by investigating its volumetric shrinkage were similar to those for the conventional, mature wood.
2. The tests of acoustic properties of 9-year-old teak wood, based on all parameters, showed that 9-year-old teak is a good material for musical instruments. This wood is characterized by a relatively high velocity of ultrasound wave, high damping of radiation attenuation and low acoustic resistance.
3. Regarding mechanical properties of 9-year-old teak wood, its MOEs value was lower than that for the conventional teak wood. On the other hand, MOR and compression strength values ware similar with the conventional one. The examined mechanical properties (MOEs, MOR, compression strength and Brinell hardness) are correlated with wood density.
4. The Brinell hardness on the longitudinal sections of juvenile teak wood is significantly lower than that of mature teak wood. This makes its use rather because of the high proportion of sapwood in the 9-year-old teak trunk. The type of damage to the samples after testing also indicates the worse mechanical properties of sapwood.

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Streszczenie: *Badania wybranych właściwości drewna tekowego z dziewięcioletniej plantacji z Indonezji*. *Tectona grandis* L.f. należy o grupy najpopularniejszych gatunków plantacyjnych drzew w krajach tropikalnych i subtropikalnych, w tym w Indonezji. Doskonałe właściwości (potwierdzone licznymi badaniami) ma dojrzałe, ok. 80-90-o letnie drewno teakowe. Jest to jednak zbyt długi okres, bowiem typowy cykl plantacyjny zwykle zamyka się w okresie do 20-25 lat. W ramach niniejszej pracy zbadano młodociane drewno z 9-o letniego drzewa teakowego i odniesiono je do danych drewna dojrzałego. Porównanie to upoważnia do stwierdzenia, że młodociane drewno teakowe nie odbiega znacząco swoimi właściwościami fizycznymi i mechanicznymi od drewna dojrzałego, jednak jest istotnie słabsze np. ma wyraźnie niższą twardość (tym samym nie we wszystkich zastosowaniach stanowi jego pełnowartościowy zamiennik). Ograniczeniem w różnych zastosowaniach pozostają: mniejsze wymiary pnia i tym samym pozyskanej z niego tarcicy oraz znaczący udział drewna bielastego o wyraźnie gorszych właściwościach w porównaniu do drewna twardzieli.

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